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Common vs. independent limb control in sequential vertical aiming: The cost of potential errors during extensions and reversals

Common vs. independent limb control in sequential vertical aiming:

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Abstract

The following study explored movement kinematics in two-component aiming contexts that were intended to modulate the potential cost of overshoot or undershoot errors in up and down directions by having participants perform a second extension movement (Experiment 1) or a reversal movement (Experiment 2). For both experiments, the initial movement toward a downward target took longer, and had lower peak acceleration and peak velocity than upward movements. These movement characteristics may reflect a feedback-based control strategy designed to prevent energy-consuming limb modifications against gravitational forces. The between-component correlations of displacement at kinematic landmarks (i.e., trial-by-trial correlation between the first and second components) increased as both components unfolded. However, the between-component correlations of extensions were primarily negative, while reversals were positive. Thus, movement extensions appear to be influenced by the use of continuous on-line sensory feedback to update limb position at the second component based on the position attained in the first component. In contrast, reversals seem to be driven by pre-planned feedforward procedures where the position of the first component is directly replicated in the second component. Finally, the between-component correlations for the magnitude of kinematic landmarks showed that aiming up generated stronger positive correlations during extensions, and weaker positive correlations toward the end of the first component during reversals. These latter results suggest the cost of potential errors associated with the upcoming second component directly influence the inter-dependence between components. Therefore, the cost of potential errors is not only pertinent to one-component discrete contexts, but also two-component sequence aims. Together, these findings point to an optimized movement strategy designed to minimize the cost of errors, which is specific to the two-component context.

Keywords: sequential aiming; movement optimization; feedforward; feedback

PsychINFO classification: 2330

1. Introduction

The two-component model of goal-directed aiming (Woodworth, 1899), and subsequent extensions of this model (Elliott, Helsen, & Chua, 2001), suggest manual aiming consists of two distinct phases: an *initial impulse* designed to place the limb within the vicinity of the target, followed by a slowed *current control* phase designed to 'home-in' on the target by using online sensory feedback. According to the optimized submovement model (Meyer, Abram, Kornblum, Wright, & Smith, 1988), these movement phases are coordinated so as to optimize the relationship between variability associated with ballistic movements (Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979) and the time-consuming error corrections designed to successfully land on the target. A central tenet of this optimization is that the initial submovement endpoints of goal-directed aims form a normal distribution centred on the middle of the target (Meyer et al., 1988). Although this outcome may hold for movements requiring minimal force over smaller displacements and with limited degrees-of-freedom (wrist rotation task), it appears that for the initial primary submovement endpoint for whole-limb movements, featuring coordination of the shoulder, elbow and wrist, there is a more strategic spatial displacement of primary submovement endpoints. That is, individuals typically undershoot the target, and with trial-and-error practice, begin to coincide decreases in variability with longer movement displacements closer to the target ("sneaking-up"; Elliott, Hansen, Mendoza, & Tremblay, 2004; see also Worringham, 1991). This strategic approach reduces the potential temporal and energy costs associated with correcting a target overshoot. That is, the performer would require more time and energy to overcome the inertia associated with a zero-velocity situation at the point of a reversal.

The tendency to minimize energy was demonstrated by assisting movement of the limb via an attached elastic rubber band that required greater eccentric force to maintain the start position. In this condition, individuals begin to overshoot the target as undershooting required more effort (Oliveira, Elliott, & Goodman, 2005). However, upon removing the assistive band, presenting a more typical unassisted condition, individuals once more begin to undershoot the target. Examining a similar energy-minimizing principle, Lyons and colleagues (Lyons, Hansen, Hurding, & Elliott, 2006) had participants aim within horizontal and vertical axes so as to manipulate the gravitational forces acting upon the limb. It was shown that when aiming in the downward (vertical) direction individuals achieved a lower peak velocity and a shorter primary submovement endpoint compared to the upward direction. The tendency to exhibit less force and undershoot the target when aiming downward was suggested to reduce endpoint variability and prevent a target overshoot that would subsequently require corrections against gravity. This contrasted with overshoots in the upward direction, which although less time-efficient and more energy-consuming than undershoots, required error corrections in the direction of gravity.

Although the control of aiming to a single target (i.e., discrete one-component tasks) has been considered in light of principles of energy-minimization, it remains unclear whether or not the same constructs apply to multiple-component sequence aiming. To date, it has been shown that the addition of a second target results in a longer initiation time, reflecting the time necessary to program the additional component (Henry & Rogers, 1960; Khan, Lawrence, Buckolz, & Franks, 2006). Furthermore, it has been shown that the spatial characteristics (Adam, van der Buggen, & Bekkering, 1993; Sidaway, Sekiya, & Fairweather, 1995) and sensory information (Ricker et al., 1999; Lavrysen, Helsen, Elliott, & Adam, 2002) associated with the later component can have overriding consequences on how individuals prepare and execute movements within earlier portions of the sequence (i.e., inter-dependency). These findings have led to suggestions that sequential aiming movements are a pre-planned composition of individual components that are released during movement execution (Adam et al., 2000). Thus, the integration of multiple components within a sequence changes underlying sensorimotor processing, and with that, the unfolding movement trajectory compared to more discrete one-component aims. This, in turn, may alter the costs associated with correcting certain types of end-point errors. For instance, in the context of two-component extension aims in the vertical axis, an overshoot at the first target may result in a costly movement reversal if the participant compensates by reducing the amplitude of the second component. Therefore, the preparation of a second movement component may alleviate the cost of overshoot errors at the first target. That is, the limb may be prepared for a second movement component following completion of the first, without comprehending the need for time- and energy-consuming corrections.

Alternatively, for one-component aims, we would expect a series of slowed mechanical oscillations designed to offset the limb at target position, and thus a greater need to consider the cost of an overshoot.

2. Experiment 1

2.1 Introduction

To examine how the tendency to minimize potential errors during goal-directed aiming influences sensorimotor processing and control, we had participants execute a series of aims that either alleviated or exacerbated the cost of potential errors by way of moving up and down in one- and two-component contexts. We reasoned that overshoot errors in the typical one-component context would be more costly for moving down than when moving up due to the required corrections working against gravitational forces acting on the limb (Lyons et al. 2006). Moreover, based on the notion that the cost of overshoot errors is reduced when the direction of overshoots (e.g., down) correspond with the movement direction to the second target (e.g., down), we expected that the impact of movement direction would be modulated as a function of the number of movement components. More specifically, we predicted movement kinematics featuring a higher initial impulse, as indicated by a greater magnitude of peak acceleration and peak velocity, and a longer movement displacement, during two-component trials compared to one-component trials, and that these differences in magnitude and displacement would be exaggerated when moving down as opposed to up. In addition, given the integration of multiple-component movements is dependent upon the spatial characteristics that are the sum of its component parts (see Khan, Helsen, & Franks, 2010), we explored the relationship between components of the two-component sequences as a function of moving in the up and down direction.

2.2 Method

2.2.2 Participants

Fifteen males and one female from Liverpool John Moores University (age range = 20-30 years, height *M* = 178.5cm *SD* = 8.5cm), agreed to take part in the study. All participants were self-declared right-handed, and had normal or correct-to-normal vision with no history of neurological disorders. The study was designed and conducted in accordance with the Declaration of Helsinki and was approved by the local ethics committee.

2.2.3 Apparatus and procedure

The apparatus consisted of a wall-mounted LCD monitor (54-cm diagonal; 154cm from ground-to-screen centre) with a spatial resolution of 1600 x 1200 pixels, and refresh rate of 85Hz. The visual stimuli were generated in MATLAB (The Mathworks, Inc) using the Cogent 2000 toolbox (www.vislab.ucl.ac.uk/cogent.php). Participants stood directly in front of the stimulus display, which was covered with a sheet of 5-mm thick transparent Plexiglas. An infrared emitting diode (IRED) was attached the tip of the dorsal side of the distal phalange of the right index finger. Finger-tip position was recorded using a 3D Investigator Motion Capture System (Northern Digital Inc., Ontario, Canada) sampling at 200Hz. Prior to each trial, participants were instructed to prepare their arm posture by positioning the index finger over a grey home position at screen centre. Following a random foreperiod (200-800ms), one or two red targets (10mm) were presented for a period of 2000ms. At the end of a trial the target(s) was extinguished, and participants relaxed the limb by returning it to their side for an inter-trial interval of 5000ms. In one-component trials, only a single target was presented at 80mm (near) or 160mm (far) above or below the home position (Figure 1A). For two-component trials, two targets, one at 80mm and the other at 160mm, on the same side of the home position were presented simultaneously in either the above or below location. In the event of a single target presentation, participants were instructed to execute a one-component aimed response as fast-and-accurate as possible. For the appearance of two targets, a two-component sequential aimed response was required involving an immediate arm movement extension after completion of the aiming movement toward the first target. In all aiming conditions, participants were required to move to the target(s) without keeping the limb in contact with the aiming surface (i.e., without sliding). There were 10 blocks of 12 trials, consisting of 20 trials per condition. There were 6 conditions, formed from the combination of direction, target distance and component (upward near one-component, downward near one-component, upward far one-component, downward far one-component, upward two-component, downward two-component). The 6 conditions were randomly presented twice within each block under the caveat that no single combination could appear on two consecutive trials.

2.2.4 Dependent variables and analysis

Three-dimensional position data were filtered using a second-order Butterworth filter at a low-pass cut-off frequency of 8Hz. Data were then differentiated and double-differentiated to obtain velocity and acceleration within the primary movement (y) axis. Movement onset was determined when velocity was above +10mm/s for upward movement and below -10mm/s for downward movement, and remained so for at least 40ms (8 consecutive samples). Movement offset was determined by the first moment velocity was less than +10mm/s for upward movement and greater than -10mm/s for downward movement, and remained so for at least 40ms. For two-component trials, the end of the first component was initially marked as the first velocity sample to be less than +10mm/s for upward movement or greater than -10mm/s for downward movement. Providing these velocities were maintained for a further 40ms, this was considered to be movement offset to the first target. In the event of a movement reversal to correct for an initial target overshoot (i.e., velocity <-10mm/s for upward movement or >+10mm/s for downward movement), we identified the end of the movement at the point where velocity returned to zero. The next instance at which the velocity was greater than +10mm/s or less than -10mm/s, for up and down movements respectively, and remained so for the 40ms temporal window marked the beginning of the second component.

Performance was measured in the form of endpoint accuracy and dispersion using constant error (CE) and variable error (VE), in addition to reaction time (RT; time difference between stimulus onset and movement onset) and movement time (MT; time difference between movement onset and movement offset). For the kinematic variables in the first component, we assessed measures of time [time to peak acceleration (PA), time to peak velocity (PV), time to peak deceleration (PD), dwell time (DT; time difference between movement offset of the first component and movement onset of the second component)], displacement [displacement at PA, displacement at PV, displacement at PD, displacement at movement end (END)] and magnitude (PA, PV PD). Given the study objectives, combined with our incentive to uphold a symmetrical factorial experimental design, the main point of interest was movement toward the near target (one- and two-component contexts). Thus, analyses on measures of time and magnitude for the near target movements involved 2 Direction (up, down) x 2 Component (one-component, two-component) repeated-measures ANOVAs. For measures of displacement to kinematic landmarks, data were analysed using a 2 Direction (up, down) x 2 Component (one-component, two-component) x 4 Kinematic landmark (PA, PV, PD, END) repeated-measures ANOVA. Tukey HSD post hoc procedures were used to decompose any significant effects ($p < .05$).

For sequential aiming trials only, we also determined mean between-component correlation coefficients as a measure of online limb control across movement components. That is, the displacement reached at kinematic landmarks, as well as their actual magnitude, in the first component were correlated on a trial-by-trial basis with kinematic landmarks in the second component. The resulting correlation coefficients were *z*-transformed prior to inferential analyses. The use of these z-scores was intended to explore the extent to which participants used online sensory feedback acquired within the first movement component to subsequently update the movement executed in the second component. Typically, strong negative correlations are synonymous with an enhanced use of online sensory feedback, whilst weak, or positive correlations, reflect feedforward limb-control (see Khan, Sarteep, Mottram, Lawrence, & Adam, 2011). For example, if the limb is moved with a higher magnitude of peak acceleration and peak velocity, and thus travels further than the target in the first component, an adjustment should be made to reduce the displacement of the second component in order to reach the second target. This type of adjustment would be reflected by a strong negative correlation. However, if fewer adjustments are made to the second component, there would be an overshoot error toward the second target, and thus a weak or positive correlation, between the two components. Fisher *z*-scores for displacement measures were analyzed using a 2 Direction (up, down) x 4 Kinematic-1 (PA-1, PV-1, PD-1, END-1) x 4 Kinematic-2 (PA-2, PV-2, PD-2, END-2) repeated-measures ANOVA. Similarly, the Fisher *z*-scores for magnitude of each kinematic event were analyzed using a 2 Direction (up, down) x 3 Kinematic-1 (PA-1, PV-1, PD-1) x 3 Kinematic-2 (PA-2, PV-2, PD-2).

To examine the specific feedforward- and feedback-based contributions *within* a component, we correlated the displacement travelled to kinematic landmarks with the distance travelled after kinematic landmarks until the movement terminated. Following a similar principle to the between-component correlations, online corrections would be demonstrated by strong negative correlations, as the greater displacement travelled to a kinematic landmark must be compensated for by shortening the displacement travelled after the kinematic landmark in order to 'home-in' on the end target (Elliott, Binsted, & Heath, 1999; Westwood, Heath, & Binsted, 2004). These within-component correlations were analysed using a 2 Direction (up, down) x 2 Component (one-component, two-component) x 3 Kinematic landmark (PA, PV, PD) repeated-measures ANOVA. For both between- and within-component analyses, we used the Tukey HSD post hoc procedure to examine the specific differences between the *z*-score means. We adjusted the Studentized Range Statistic associated with the calculation of the Tukey's critical value so that as well as comparing the means to each other, we could also use the critical value to compare them to a theoretical value of zero. For all statistical analyses, significance was declared at $p < 0.05$.

2.3 Results

2.3.1 Performance measures

For performance measures, there were no significant main effects, nor an interaction, for RT and CE (*ps* > 0.05). For variable error, there was a significant main effect of Direction ($F(1, 15) = 15.60$, $p < 0.05$) and Component ($F(1, 15) = 10.98$, $p < 0.05$), as well as a significant Direction x Component interaction ($F(1, 15) = 6.28$, $p < 0.05$). Variability of movement endpoints for downward aims in the two-component trials ($M = 8.7$mm) were greater than that of the one-component trials ($M = 5.4$mm), while for upward aims there was no significant difference between one-component (*M* = 4.7mm) and two-component trials (*M* = 4.7mm). For movement time, there was a significant main effect of Direction only ($F(1, 15) = 33.56$, $p < 0.05$), with shorter times for upward compared to downward aims (Figure 2).

2.3.2 Kinematic measures

The direction effect for movement time was at least partially explained by main effects for time to peak acceleration ($F(1, 15) = 24.79$, $p < 0.05$) (up: *M* = 45ms; down: *M* = 66ms) and time to peak velocity ($F(1, 15) = 84.14$, $p < 0.05$) (up: *M* = 108ms; down: *M* = 149ms), both of which occurred earlier for upward compared to downward aims. There was no significant difference between upward (*M* = 72ms) and downward (*M* = 74ms) aims for the dwell time ($t(15) = -0.31$, $p > 0.05$).

For displacement at kinematic landmarks, there was a significant main effect of Direction ($F(1, 15) = 26.36$, $p < 0.05$), and a significant Direction x Kinematic landmark interaction ($F(3, 45) = 19.57$, $p < 0.05$) (Table 1). For upward aims, peak acceleration, peak velocity and peak deceleration occurred at shorter movement displacements than downward aims. Moreover, there was a significant Direction x Component x Kinematic landmark interaction ($F(3, 45) = 4.51$, $p < 0.05$) indicating less movement displacement at peak deceleration for upward aims in the one-component compared to the two-component trials.

The analyses for the magnitude of kinematic landmarks also revealed a significant main effect of Direction for peak acceleration ($F(1, 15) = 97.21$, $p < 0.05$) and peak velocity ($F(1, 15) = 13.47$, $p < 0.05$), which were both higher for upward (PA: *M* = 7.73m/s^2; PV: *M* = 512mm/s) compared to the downward aims (PA: *M* = 5.05m/s^2; PV: *M* = 466mm/s). Moreover, there was a significant Direction x Component interaction for peak acceleration ($F(1, 15) = 6.12$, $p < 0.05$), with a greater peak for upward aims in the one-component trials (up: *M* = 7.85m/s^2; down: *M* = 4.99m/s^2) compared to the two-component trials (up: *M* = 7.61m/s^2; down: *M* = 5.11m/s^2)[1].

2.3.3 Between-component correlations

For the correlations on displacement at kinematic landmarks, it appeared there was a steady increase in the negative correlations between the two components as both movements progressed toward the end. Indeed, the analysis revealed there was a main effect for both Kinematic-1 ($F(3,45) = 34.47$, $p < 0.05$), and Kinematic-2, ($F(3,45) = 17.81$, $p < 0.05$), and more noteworthy, a Kinematic-1 x Kinematic-2 interaction ($F(9,135) = 7.33$, $p < 0.05$) (Figure 3). The Tukey critical value for Kinematic-2 at each level of Kinematic-1 was .14, and thus any z-score of .14, or greater, was also significantly different from zero. For the displacement at PA-1, there was no significant relationship with any landmarks of the second component. The displacement at PV-1 was reliably related to the displacements at PD-2 and END-2. Moreover, the displacement at PV-1 was significantly more related to the displacements at PV-2, PD-2 and END-2 than PA-2, while the relation between the displacement at PV-1 and the displacement at END-2 was significantly greater than with displacements at PV-2 and PD-2, which were not significantly different from each other. A similar pattern was evident for displacement at PD-1, for which there were significantly more robust relations with displacements at PV-2 and END-2 compared to PA-2, whilst relations with PV-2 and PD-2 were significantly less reliable than END-2. For the displacement at END-1, there was a significant relation with all displacements of the second component, although the relations shared with the displacements at PV-2 and PD-2 were greater than PA-2. Again, the correlations with displacements at PV-2 and PD-2 were not significantly different from each other, though they were significantly less related than END-2. The overall pattern of results showed there was little or no relation between the limb displacements in the two movement components at the earliest kinematic landmark (i.e., PA) and then a progressive trend toward a negative relation as the movement components progressed.

For the correlations on magnitude of kinematic landmarks, there was a significant main effect of Direction ($F(1, 15) = 5.50$, $p < 0.05$), although no significant main effect of Kinematic-1 ($F< 1$), nor Kinematic-2 ($F(2, 30) = 2.41$, $p > 0.05$). The Tukey critical value for the effect of direction was .10, thus, both upward (mean $z = .38$) and downward (mean z = .21) aims were significantly different from zero, while there were greater positive relations for upward than downward aims.

2.3.4 Within-component correlations

There was a significant main effect of Direction ($F(1, 15) = 37.93$, $p < 0.05$) indicating greater negative correlations for downward aims, and a significant main effect of Component ($F(1, 15) = 35.78$, $p < 0.05$) indicating greater negative correlations for two-component trials. Moreover, there was a significant Component x Kinematic landmark interaction ($F(2, 30) = 123.83$, $p < 0.05$), which was superseded by a Direction x Component x Kinematic landmark interaction ($F(2,30) = 3.55$, $p < 0.05$) (Figure 7A). Post hoc analysis confirmed greater negative correlations for the two-component trials in both movement directions at PA, with these differences continuing in the up direction thereafter, though the negative correlations were greater for one-component trials in the down direction at PD.

2.3.5 Far target check

To ensure participants' movements were performed accurately toward the far target in both one-component and two-component contexts, we analysed accuracy (CE) and dispersion (VE) at the far target using a 2 Direction (up, down) x 2 Component (one-component, two-component) repeated-measures ANOVA. In this respect, limited differences in the second movement component toward the far target would suggest the effects reported thus far for the first component were not a result of differences in responses toward the second target, but instead, the nature of the aiming task (i.e., movement direction, number of components). For CE, there were no significant main effects of Direction ($F(1, 15) = 0.40$, $p > 0.05$) and Component ($F(1, 15) = 2.28$, $p > 0.05$), nor a Direction x Component interaction ($F(1, 15) = 0.16$, $p > 0.05$). The lack of differences and comparatively low error scores (M = -0.7mm) suggest individuals prepared and executed a precise movement response toward the far target in the two-component context. Thus, any implications derived from the one-component analyses were coincident with accurate preparation of the second component. Meanwhile, for VE, there was a significant main effect of Direction ($F(1, 15) = 13.94$, $p < 0.05$), and Component ($F(1, 15) = 28.40$, $p < 0.05$), as well as a Direction x Component ($F(1, 15) = 4.84$, $p < 0.05$) interaction. Post hoc comparisons confirmed that there was greater variability in both up and down directions for the one-component (up: M = 5.8mm; down: M = 8.8mm) compared to the two-component trials (up: M = 4.1mm; down: M = 5.0mm). These findings align with suggestions that greater movement displacement, as in the one-component movement toward the far target, is associated with increased movement variability (Schmidt et al., 1979). Moreover, these analyses are consistent with the idea that online control prior to or during the second movement component had the effect of reducing endpoint dispersion.

2.4 Discussion

For both one- and two-component responses, movement time and time to kinematic landmarks when aiming to the first target were reduced in the upward compared to downward direction, and coincided with higher peak acceleration and peak velocity. This resulted in similar endpoint accuracy, although there was lower variability at the near target in the upward compared to downward aiming direction. Thus, upward aims featured a greater impulse than downward aims, which was likely a result of increased contributions from feedforward planning procedures (efference) (Elliott et al., 2010; Hansen, Glazebrook, Anson, Weeks, & Elliott, 2006; Khan, Franks, & Goodman, 1998). This pattern of results is consistent with our original suggestion of individuals accommodating the cost of potential target overshoots by providing a low magnitude initial impulse when aiming downwards, as an overshoot in this instance would require more energy-consuming corrections against gravitational forces (Lyons et al., 2006).

The between-component correlations for displacement measures at kinematic landmarks showed negative relations between the first and second component. This indicates that the displacement reached in the first component was subsequently compensated for in the second component. Moreover, there was evidence of an increasing impact of displacement attained at mid-late portions of the first component on the mid-late portions of the second component.

In addition, the between-component correlations for magnitude of kinematic landmarks revealed more positive relations for the upward than downward aims. This finding further supports the notion of a more pre-planned movement approach for upward aims compared to downward aims. Finally, the within-component correlations revealed increased negative relations for the two-component trials, thus revealing a greater use of online sensory feedback to correct the limb within a component, whilst concurrently controlling the limb between components. In addition to this sophisticated multi-purpose control, the extent of these online adjustments appears to be sensitive to the cost of the movement direction as the one-component trials featured increased control for the downward condition upon nearing the end of the movement (i.e., PD). Based on these findings, we next decided to consider whether the influence of the vertical movement direction on aiming movements embedded into a sequence is in fact a function of the initial movement direction, or the forthcoming direction of the second component.

3. Experiment 2

3.1 Introduction

The findings of Experiment 1 suggest that to minimize the cost of making downward overshoot errors, participants adopt a control strategy designed to enhance the use of online sensory feedback in one-, as well as two-component contexts. This strategy resulted in similar endpoint accuracy for both movement directions. Nonetheless, it remains to be seen whether the influence upon extension sequence aims is due to the cost associated with the first, second or both component directions. The second experiment was designed to examine this point by dissociating the movement directions, and thus the impact of potential overshoots in the first component upon that of the second. Following this rationale, two-component aims were performed in which the first movement was followed by a reversal movement back toward the home position in the second component. Notably, in reversal sequence aims, there is a potential advantage associated with the movement dynamics of the transition between components. That is, the same muscle groups used to decelerate the first movement (i.e., antagonists) can be exploited to move the limb back toward the home position (i.e., agonist) for the second movement (Adam et al., 1993; Guiard, 1993; Savelberg, Adam, Verhaegh, & Helsen, 2002). Thus, the preparation of movement components becomes more easily integrated (Khan, Tremblay, Cheng, Luis, & Mourton, 2008), and could reasonably result in errors in the first component influencing the second component. For instance, while a low magnitude and long duration initial impulse could be exhibited upon initially moving down, the degree of integration, as primarily indicated by the strength of between-component correlations, could be decreased when the following second component requires a downward movement as it potentiates a greater cost to the moving limb. That is, the relation between components may be underpinned by the cost associated with the upcoming second component, in addition, or as opposed to, the movement direction of the first component.

3.2 Method

3.2.1 Participants

Thirteen males and one female from Liverpool John Moores University (age range of 20-30 years, height *M* = 178.5cm. *SD* = 7.8cm)[2] agreed to take part in the study. All participants were self-declared right-handed, and had normal or correct-to-normal vision with no history of neurological disorders. The study was designed and conducted in accordance with the Declaration of Helsinki and was approved by the local ethics committee.

3.2.2 Apparatus and procedure

The apparatus and experimental setup were the same as Experiment 1. In order to control for the spatial location, the grey home position was adjusted to appear at screen centre, 80mm below screen centre (lower spatial location) or 80mm above screen centre (higher spatial location). With these start locations, upward and downward limb movements could be spatially matched (or mismatched) with respect to the aiming surface (see Figure 1B). For instance, we could conceivably have upward and downward movements within the same area of the screen. The inclusion of these locations enabled us to further examine the potential role of different viewing perspectives imposed by movements in the up and down direction. For example, if the direction effects found in Experiment 1 were an artefact of viewing perspective, the impact of direction should be exaggerated when moving toward the most extreme target location. That is, the general differences in movement direction would no longer occur, unless the movements are executed within the high and low spatial locations for the up and down directions respectively. Upon trial onset, a red target was presented 80mm above or below the home position. When a single red target was presented, participants were required to execute a one-component aim as fast-and-accurate as possible. Alternatively, when a red target was presented in tandem with the home position that changed colour from grey to red, a two-component sequential aimed response was required. This involved moving to the first target followed by a reversal toward the home position that now acted as the second target. The spatial location and direction of the movement responses were randomised with the caveat that no single combination of location and direction could appear on two consecutive trials, whilst one- and two-component trials were blocked in order to prevent any difficulty in discerning single and sequential movement trial requirements. There were 8 blocks of 20 trials per stimulus presentation (upward high one-component, downward high one-component, upward low one-component, downward low one-component, upward high two-component, downward high two-component, upward low two-component, downward low two-component). Note that any references to direction (up/down) are specific to the movement direction of the *first* component as this was of primary interest for our initial performance and kinematic measures.

3.2.3 Dependent variables and analysis

The data processing and reduction procedures followed the same principles as Experiment 1. However, the analysis of performance and kinematic measures in the first component featured an additional factor of spatial location such that timing, magnitude and outcome variables were subject to a 2 Direction (up, down) x 2 Component (one-component, two-component) x 2 Location (higher, lower) repeated-measures ANOVA, whereas displacement variables were subject to a 2 Direction (up, down) x 2 Component (one-component, two-component) x 2 Location (higher, lower) x 4 Kinematic landmark (PA, PV, PD, END) repeated-measures ANOVA. For the sake of clarity, combined with the null effects of location for timing, magnitude and dispersion, and the relatively scarce influence of location on displacement and endpoint accuracy (see below), the between-component correlations were collapsed across spatial locations. Thus, the between-component correlations were analysed as per Experiment 1. The within-component correlations for the first movement component were analysed with a 2 Direction (up, down) x 2 Component (one-, two-component) x 2 Location (higher, lower) x 3 Kinematic landmark (PA, PV, PD) repeated-measures ANOVA.

3.3 Results

3.3.1 Performance measures

For RT, there was a significant Direction x Location interaction ($F(1, 13) = 30.15$, $p < 0.05$). Post hoc analysis revealed a shorter RT for upward aims in the lower spatial location (*M* = 258ms) compared to the higher location (*M* = 272ms). The reverse was evident for downward aims with a shorter RT in the higher spatial location (*M* = 258ms) compared to the lower location (*M* = 274ms). Thus, RT was shorter when the initial movement was toward the centre of the screen. The Direction x Component x Location interaction approached conventional levels of significance ($F(1, 13) = 4.65$, $p = 0.06$) indicating the RT advantages when moving toward the centre of the screen were more robust in two-component (up low: *M* = 258ms vs. up high: *M* = 284ms; down high: *M* = 252ms vs. down low: *M* = 280ms) compared to one-component trials (up low: *M* = 258ms vs. up high: *M* = 272ms; down high: *M* = 258ms vs. down low: *M* = 274ms). For CE, there was a significant main effect of Direction ($F(1, 13) = 7.89$, $p < 0.05$), and a significant Direction x Location interaction ($F(1, 13) = 9.42$, $p < 0.05$). There were greater undershoot errors for upward aims in the higher spatial location (up: *M* = -0.6mm; down: *M* = -1.4mm) than the lower spatial location (up: *M* = 1.2mm; down: *M* = -2.7mm). For variable error, there was a significant main effect of Direction ($F(1, 13) = 6.60$, $p < 0.05$), indicating lower variability for upward (*M* = 4.5mm) compared to downward (*M* = 5.6mm) aims. There were no significant main effects, nor any interactions featuring Component and Location (*ps* > 0.05). Meanwhile, for MT, there was a significant main effect of Direction ($F(1, 13) = 16.86$, $p < 0.05$) with upward aims taking more time than downward aims (Figure 4). Furthermore, there was a significant main effect of Component with shorter MTs for the two-component (M = 373ms) compared to the one-component (M = 399ms) trials.

3.3.2 Kinematic measures

Measures of time to kinematic landmarks: peak acceleration ($F(1, 13) = 44.17$, $p < 0.05$) (up: M = 46ms; down: M = 82ms), peak velocity ($F(1, 13) = 84.54$, $p < 0.05$) (up: M = 122ms; down: M = 161ms) and peak deceleration ($F(1, 13) = 16.79$, $p < 0.05$) (up: M = 233ms; down: M = 259ms); occurred earlier when aiming up compared to down suggesting the greater overall time for upward aims was reflective of more time spent in the late 'homing-in' phase (i.e., time after peak deceleration). In addition, the time to peak deceleration analysis revealed a significant main effect of Component ($F(1, 13) = 7.31$, $p < 0.05$). Peak deceleration occurred earlier for the one-component (M = 240ms) compared to the two-component aims (M = 253ms) suggesting the two-target movement time advantage (i.e., shorter movement times to the first target during two-component reversal aims compared to one-component aims; Adam et al., 1993) might also be attributed to the late 'homing-in' phase. Finally, for dwell time, there was a significant main effect of Direction ($F(1, 13) = 8.93$, $p < 0.05$) (up: M = 77ms; down: M = 116ms), and Location ($F(1, 13) = 11.62$, $p < 0.05$) (higher: M = 93ms; lower: M = 101ms).

For displacement at kinematic landmarks, there was a significant main effect of Direction ($F(1, 13) = 4.70$, $p < 0.05$), and a significant Direction x Kinematic landmark interaction ($F(3, 39) = 22.76$, $p < 0.05$) (Table 2). Displacement at peak acceleration and peak velocity was less for the upward than the downward aims, although this effect was reversed at peak deceleration and the end of the movement. Moreover, there was a significant Direction x Location x Kinematic landmark interaction ($F(3, 39) = 4.53$, $p < 0.05$), which confirmed the reverse effect of direction at peak deceleration took place primarily at the lower spatial location (up low: M = 70.5mm vs. down low: M = 67.1mm; up high:

M = 69.4mm vs. down high: M = 68.7mm), although further differences in direction reported across kinematic landmarks were consistent throughout spatial locations. Finally, there was a significant Component x Kinematic landmark interaction ($F(3, 39) = 2.86$, $p < 0.05$), with less movement displacement at peak deceleration for one-component compared to the two-component trials.

Analysis of the magnitude of kinematic landmarks revealed a significant main effect of Direction for peak acceleration ($F(1, 13) = 42.99$, $p < 0.05$) and peak velocity ($F(1, 13) = 6.96$, $p < 0.05$), with higher values exhibited for the upward (PA: $M = 6.34m/s^2$; PV: M = 465mm/s) than the downward aims (PA: $M = 4.47m/s^2$; PV: M = 437mm/s). In addition, there was a significant main effect of Component ($F(1, 13) = 5.86$, $p < 0.05$) for the magnitude of peak acceleration, with higher values for the one-component ($M = 5.60m/s^2$) compared to the two-component trials ($M = 5.21m/s^2$). The magnitude of peak deceleration analysis revealed no significant effects ($ps > 0.05$)[3].

3.3.3 Between-component correlations

The most notable feature of the correlations on displacement at kinematic landmarks was a positive relationship between the first and second components (Figure 5). This finding is in contrast to the negative relations in the extension sequences of Experiment 1. The analysis of displacement measures showed, once again, significant main effects for both Kinematic-1 ($F(3,39) = 41.21$, $p < 0.05$), and Kinematic-2 ($F(3,39) = 20.50$, $p < 0.05$). Moreover, there was a Kinematic-1 x Kinematic-2 interaction ($F(9,117) = 8.74$, $p < 0.05$). The Tukey critical value for examining Kinematic-2 at each level of Kinematic-1 was .12. As is evident in Figure 5, there was increased covariation between the limb displacements as the two-component movement unfolded, with the displacements at PV-1, PD-1, END-1 positively relating with the corresponding landmarks in Kinematic-2. Moreover, the relations for displacements at PV-1 and PD-1, with landmarks in Kinematic-2, were not significantly different from one another, which unlike Experiment 1, suggests the relations with Kinematic-2 were equally robust. However, for correlations involving END-1 there was an increasing positive relation with the displacements as the movement unfolded from PV-2 and PD-2 to the displacement at END-2. In summary, it appears that in a reversal aiming context, individuals prepare for the mid-late portions of two movement components in a common, inter-dependent, fashion.

The magnitude analysis revealed a Direction x Kinematic-1 interaction ($F(2, 26) = 4.56$, $p < 0.05$) (Figure 6). The Tukey critical value for the effect of direction was .10, thus there were significant positive correlations, relative to a theoretical value of zero, between the magnitude of PA-1 and PV-1 and kinematic landmarks of the second component in both up and down directions. In addition, the magnitude of PD-1 for the downward direction only was significantly related to magnitudes of kinematic landmarks in the second component. Finally, there were significantly fewer positive relations for the magnitude of PD-1 in the up compared to down direction. Therefore, at least toward the end of the first movement component in the upward direction and prior to the reversal, individuals prepare to move the limb given the constraints of the forthcoming movement direction of the second component (i.e., down).

3.3.4. *Within-component correlations*

For the within-component correlations, there was a significant main effect of Direction ($F(1, 13) = 15.91$, $p < 0.05$), and Kinematic landmark ($F(2, 26) = 71.04$, $p < 0.05$), although these effects were superseded by a Direction x Kinematic landmark interaction ($F(2, 26) =48.51$, $p < 0.05$) (Figure 7B). Post hoc analysis revealed the distance to PA was more negatively correlated with the distance travelled after PA for the down compared to the up direction. Upon reaching PD however, there was a reverse effect, with more negative correlations evident in the up compared to down direction.

3.3.5 Second target check

To ensure the outcome of the above analyses were based upon the accuracy of movement responses for the second movement component, and to remain consistent with the analyses of Experiment 1, we analysed accuracy (CE) and dispersion (VE) at the second target using a 2 Direction (up, down) x 2 Component (one-component, two-component) x 2 Location (high, low) repeated-measures ANOVA. For CE, there was a significant Direction x Component interaction ($F(1, 13) = 7.53$, $p < 0.05$), and a Direction x Component x Location interaction ($F(1, 13) = 7.80$, $p < 0.05$). However, post hoc analyses on matched movement endpoints (up one-component low ($M = 0.6$mm) vs. down two-component low ($M = 2.1$mm), down one-component low ($M = -1.7$mm) vs. up two-component low ($M = -1.9$mm), up one-component high ($M = -1.1$mm) vs. down two-component high ($M = 0.3$mm), down one-component high ($M = -1.2$mm) vs. up two-component high ($M = -1.4$ mm)), revealed no significant differences between conditions ($ps > 0.05$). Thus, the three-way interaction was of no relevance to our original question. There were no significant main effects, nor interactions for VE ($ps > 0.05$; overall $M = 4.8$mm), thus indicating limited differences in dispersions across one-component and two-component trials at the final target endpoint. Therefore, movement within the second component was appropriately prepared during the first component for accurate execution in the second.

3.4 Discussion

There was a longer overall movement time to the first target for upward compared to downward aims, which occurred in combination with shorter times to peak acceleration, peak velocity, and peak deceleration for upward aims. Thus, the previously reported greater impulse for the upward aims was again evident, though it seems an extended time for ‘homing-in’ (i.e., time after peak deceleration) was adopted when participants were aiming up. This type of movement control was further evidenced by the magnitude of peak acceleration and peak velocity, which, in correspondence with Experiment 1, were higher for upward compared to downward aims. At least for some of the direction effects, there appeared to be an influence of spatial location. That is, reaction time was shorter for the up and down directions when aiming in the lower and higher spatial locations respectively. Moreover, the displacement at peak deceleration was extended for the up direction primarily when in the lower location. Notably, the impact of spatial location was restricted to situations where participants were moving toward the central target location. Indeed, the central target was in fact where most of the experimental trials unfolded, which suggests that the spatial parameters of this location were better represented than the extreme target location (top or bottom) (Boutin, Fries, Panzer, Shea, & Blandin, 2010; Hayes, Andrew, Elliott, Roberts, & Bennett, 2012). Alternatively, the differences in reaction time may indicate that it was only when starting from the most extreme target location, before heading toward the central target location, that participants knew in advance what target would be hit before trial onset. Meanwhile, when starting from the middle location, it could be the target to aim for would appear either up or down. This would clearly aid the preparation and execution of such trials granted the limited amount of information to consider during response selection and programming (Hansen et al., 2006; Henry & Rogers, 1960). Therefore, the minor role of spatial location was most likely a result of differences in the selection and programming of such responses, rather than interference caused by the viewing perspective.

Interestingly, the between-component correlations showed a substantial decrease in the positive relation between peak deceleration from the first component and kinematic landmarks from the second component when initially aiming up compared to down. As the initial impulse is highly influenced by the cost associated with overshoots, it is likely that during an initial upward movement the limb is concurrently being prepared for the subsequent downward movement. In addition, the shorter dwell times after an initial upward aim, compared to an initial downward aim, would suggest less time is required to integrate sensory feedback from the first component with the unfolding movement plan for the second component. On the other hand, for an initial downward aim, the increased dwell time before making the upward reversal could result from limiting the integration between components. Therefore, reversal sequence aims featuring an upward response in the first component ensures the processing and implementation of the response takes place early on, whilst downward responses in the first component tend to delay processing of the second component until the first is completed. In addition, the within-component correlations reflect nicely the optimization of limb control, with adjustments introduced as early as peak acceleration when moving down, whereas they were only evident at peak deceleration when moving up. The early control adopted for downward movements further emphasises the importance of upholding increased control of potentially more costly movement directions.

4. General Discussion

The current study examined the control of goal-directed aiming in different contexts that were intended to modulate the potential cost of overshoot or undershoot errors. Previous findings indicate that when a movement has the potential to generate greater endpoint variability participants tend to exhibit greater target undershooting (i.e., shorter amplitude movements; see Elliott et al., 2004; Worringham et al., 1991). This strategic undershooting is designed to avoid any time- and energy-consuming corrections associated with any overshoots. More recently, it was shown that this ‘play-it-safe’ strategy was also related to the direction of the corrective submovement (Lyons et al., 2006), with individuals typically adopting a smaller magnitude of force and shorter displacement when aiming downwards in order to avoid an overshoot that would require corrections against gravity. Here, we had participants aim in both up and down directions toward targets in one-component (single target) and two-component (two targets) contexts. The idea was that introducing an additional movement component would result in some adjustment to control of the first movement component compared to aiming at a single target because of the differential costs associated with potential errors. That is, the preparation of aimed responses in the vertical axis would not only be influenced by the costs associated with the initial movement direction (i.e., up or down), as in discrete one-component contexts, but also the direction, and subsequent costs, of a second movement component.

For both Experiment 1 and Experiment 2, lower magnitude and later occurrence of early-mid kinematic landmarks for downward compared to upward aims was consistent with previous suggestions that downward aims are adapted to minimize the threat of more costly errors associated with an overshoot. Interestingly, kinematic landmarks when aiming down were also generally achieved at greater displacements. This contrasts with Lyons et al. (2006), who reported a shorter time to primary submovement endpoints when moving down compared to up, combined with a lower magnitude of peak velocity and smaller movement displacement in the downward direction. Though the results may differ slightly, most likely as a result of differences between experimental set-ups (e.g., materials surrounding the aiming surface, additional movement component, etc.), they point to the same conclusion; that is, individuals adapt the execution of target aims based on the cost of potential errors associated with the movement outcome.

Notably, in Experiment 1, there was a greater magnitude of peak acceleration for upward aims in the one-component compared to the two-component trials. In addition, there was a shorter displacement at peak deceleration. Thus, there was a modulatory effect of component (*context effects*; Adam et al., 1993), at least when moving up. More specifically, it appears when presented with a one-component trial, individuals generate increased acceleration early within the movement trajectory, and in turn, get closer to the target earlier, thus providing more opportunity to modify limb position late in the movement. Contrary to our original hypothesis, the limited effect of component on downward aims suggests that the cost associated with potential errors in this direction carries over from a one- to a two-component context. Indeed, the cost of such an error either in the one- or two-component context may be so severe that it is avoided regardless. These suggestions were supported by the analysis of between-component correlations for the magnitude of kinematic landmarks associated with the degree of force designed to initially propel the limb forward (i.e., PA, PV) before finally decelerating to terminate limb movement at the target (i.e., PD). That is, it was shown that for downward aims there were fewer positive correlations between these kinematic landmarks compared to the upward aims. Therefore, it would appear that participants exhibited a less pre-planned inter-relation between components when moving down, at least with respect to the generation of propulsive and braking forces. Together, these findings point to an optimized movement strategy designed to minimize the cost of errors, which is specific to the two-component context.

In the context of reversal aiming sequences of Experiment 2, there was a lower positive relation between peak deceleration of the first component and kinematic landmarks of the second after executing an initial upward movement prior to downward reversal. This, combined with a shorter dwell time for the initial upward aims, would suggest individuals prepare for the upcoming downward response as early as peak deceleration in the first component. The extended overall movement time attributed to the time spent after peak deceleration when moving up would further support the view of secondary downward aims being accommodated within the less costly upward component. Meanwhile, the extended dwell time for the initial downward response prior to an upward reversal suggests individuals have to ensure an accurate end position at the first target before they can prepare and/or integrate any additional movement. Together, and to the best of our knowledge, these present the first set of results in the sequence aiming literature to suggest differences in the up-down vertical axis based on feedforward planning procedures designed to minimize energy expenditure.

Our findings regarding movement optimization of one- and two-component aims also indicate feedback- and feedforward-based control differs between extension and reversal sequence aiming respectively. For Experiment 1, we observed significant negative between-component correlations for displacement at kinematic landmarks suggesting individuals updated the limb position in the second component based on errors attained in the first component. This is consistent with the interpretation given to previous findings of increased negative relations when presented with vision compared to no vision, thus indicating the greater use of online sensory feedback (Khan et al., 2011). However, here we go one step further by attributing these feedback-based control procedures to the mid-late kinematic landmarks of the first and second components, which become more negatively related as the movement components unfold. In contrast to Experiment 1, Experiment 2 demonstrated positive between-component correlations for the displacement of kinematic landmarks between the first and second movement components. We interpret these correlations as evidence that limb position at the second component was primarily determined by feedforward planning procedures designed to ensure consistent displacements between components. We acknowledge that the positive between-component correlations might also result from the need to compensate for amplitude covered in the first component in order that the reversal movement returns to the start location. Such a compensatory strategy would involve the use of online sensory feedback available during the first movement to accommodate the execution of the second movement. If this were the case, however, one might expect a difference in the pattern of the within-component relations for single and two-component movements. That is, consistent with the findings of Experiment 1, the within-component negative relations for the first movement would be more robust under two-component conditions. In contrast to this prediction, there were fewer differences for the correlations in the first component across one- and two-component trials. Thus, it seems that while sensory feedback is important within each component, the first and second components of a reversal sequence are organized together.

These underlying control differences are consistent with suggestions that movement extensions do not share the same dynamic properties as reversals. In the case of movement reversals, there is the added benefit of converting potential energy from antagonistic muscle activity in the first component to mechanical energy at the second (Adam et al., 1993; Guiard, 1993; Savelberg et al., 2002). It is precisely these alterations in the activity pattern that provided the foundation for the commonly cited two-target movement time advantage for reversal movements (Adam et al., 1993; also see Khan et al., 2010). These suggestions were supported by the shorter time to peak deceleration for one- compared to two-component trials, thus isolating the overall two-target advantage to the late portions of the initial movement. In this instance, one-component trials feature a time-consuming triphasic activity pattern with agonistic muscle bursts toward the end of the movement that dampens the potential of initial antagonistic activity, and thus prevent a complete movement reversal. However, these muscular activation differences, and the subsequent two-target advantage, may only be maintained when the accuracy constraints are not too demanding (≤3mm width target) (Adam et al., 1993; Adam et al., 1995). Notably, with respect to the current study, target width was 10mm and thus led to a movement time advantage for the two-component trials.

We may then ask; what is the influence of components on movement time during extension sequence aims? In this instance, we might anticipate a one-target advantage due to the additional processing demands undertaken in the first component so as to implement a pre-planned movement response for the second extension (*movement integration hypothesis*; Adam et al., 2000). However, we found no such movement time advantage for one-component trials. One explanation could be related to the constraints of the task, which required vertical aiming movements to be performed on a Plexiglas aiming surface. This differs from previous sequence aiming studies reporting a one-target advantage, where movements were performed in the horizontal axis using a push-button apparatus (see Khan et al., 2010 for a discussion). An alternative explanation is that the limited movement time differences were due to the trial procedure adopted in Experiment 1. That is, the one- and two-component trials were fully randomized, and were not preceded by pre-cues. This would have necessitated a decision to be made upon target presentation, which has been shown to minimize movement time advantages compared to single-choice scenarios (Khan et al., 2006). This same reason could also explain why differences in reaction time failed to unfold. That is, the shorter reaction times typically reported for single- compared to multi-choice scenarios were not present in Experiment 1 because individuals were unaware of the upcoming trial. The absence of these fundamental response differences has in fact been isolated to knowledge of the number of components, and not necessarily the required movement amplitude (Khan, Mourton, Buckolz, & Franks, 2008). However, we did find some differences in movement time between one- and two-component trials in Experiment 2 where trial order was blocked, meaning that participants were most likely aware of the number of components prior to target onset. The results however showed limited differences in reaction time between one- and two-component trials. Notably, the absence of such reaction time differences is not without precedence when it comes to reversal sequence aims. Indeed, following preparation of a two-component reversal, it has been shown there is a clear advantage in movement time compared to only one-component, whilst there are limited differences when it comes to reaction time (Khan, Tremblay, et al., 2008; Experiment 2). Thus, the differences in the movement dynamics in reversal sequences and one-component aims may not translate to the same degree for a measure of response selection and programming. Still, it is important to consider that in spite of these limited reaction and movement time differences, the execution of sequence aims was consistent with minimizing the cost of potential errors (Elliott et al., 2004; Lyons et al., 2006), and the utilisation of online sensory feedback to correct limb position both within and between components (Khan et al., 2011; Lavrysen et al., 2002). Future experiments exploring the common vs. independent limb control during sequential vertical aims would do well to examine the potential interaction between energy minimization and differences in response programming.

In summary, we found clear evidence to support the notion of underlying differences between aiming in the up and down directions, in both single-component and two-component contexts. We attribute these differences, which are consistent with more reliance on feedforward planning for upward movements as opposed to the slowed feedback-controlled downward movements, to the minimization of costly errors in the event of a target overshoot. Finally, there were underlying control differences between extension and reversal sequence aims. Extension sequence aims feature more feedback-based control, wherein visual information is used to correct limb position errors both within and between movement components, whilst reversal sequence aims operate primarily through integrated feedforward control.

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Figure captions

Figure 1. The *dotted white* lines depict the direction of the first of one- or two-component aims, and *solid white* lines depict the direction of a single movement component. The *grey* circles depict the home position and *red* circles depict the target location. (A) (i) Up-near, (ii) down-near, (iii) up-far, and (iv) down-far target configurations for Experiment 1. (B) The *dotted red* circles depict the second target location in the event of a two-component trial. (i) Up-high, (ii) down-high, (iii) up-low, and (iv) down-low target configurations for Experiment 2.

Figure 2. Time to peak acceleration (*PA*), peak velocity (*PV*), peak deceleration (*PD*) and total movement time (*MT*) (ms) as a function of direction (*up, down*) and component (*1,* 2) for Experiment 1. Error bars represent standard error of the mean.

Figure 3. Fisher *r*- to *z*-transformed between-component correlation coefficients for displacement at kinematic landmarks (*PA, PV, PD, END*) in the first (lower axis) and second component (upper axis) of Experiment 1. Error bars represent standard error of the mean. (*) represents a significant difference from a theoretical value of zero.

Figure 4. Time to peak acceleration (*PA*), peak velocity (*PV*), peak deceleration (*PD*) and total movement time (*MT*) (ms) as a function of direction (*up, down*) and component (*1,* 2) for Experiment 2. Error bars represent standard error of the mean.

Figure 5. Fisher *r*- to *z*-transformed between-component correlation coefficients for displacement at kinematic landmarks (*PA, PV, PD, END*) in the first (lower axis) and second component (upper axis) of Experiment 2. (*) represents a significant difference from a theoretical value of zero.

Figure 6. Fisher r-to z-transformed between-component correlation coefficients for magnitude at kinematic landmarks (PA, PV, PD, END) in the first component as a function of movement direction (up, down) of Experiment 2. Error bars represent standard error of the mean. (*) represents a significant difference from a theoretical value of zero.

Figure 7. Fisher *r*- to *z*-transformed within-component correlation coefficients for displacement at kinematic landmarks (*PA, PV, PD, END*) in the first component of Experiment 1 (A) and Experiment 2 (B).

Table1. Mean displacement (mm) (±SE) to kinematic landmarks (*PA, PV, PD, END*) as a function of direction (*up, down*) and component (*1, 2*) for Experiment 1.

Table 2. Mean displacement (mm) (±SE) to kinematic landmarks (*PA, PV, PD, END*) as a function of direction (*up, down*) and component (*1, 2*) for Experiment 2.

Footnotes

1. Correlations between participant height and kinematic measures within the first component for the up one-component, down one-component, up two-component and down two-component (i.e., movement time, displacement to peak acceleration, time to peak acceleration, time to peak velocity, magnitude of peak acceleration and magnitude of peak velocity) revealed no significant relationship for all analyses (Pearson's *r* ranges = -.40 to .28, *ps* > .05).
2. The height of 11 out of the 14 participants was recorded.
3. Correlations between participant height and kinematic measures within the first component for the up one-component, down one-component, up two-component and down two-component at low and high spatial locations (i.e., reaction time, constant error movement time, time to peak acceleration, peak velocity, and peak deceleration, displacement at peak acceleration, peak velocity, peak deceleration, movement end, and magnitude of peak acceleration and peak velocity) revealed no significant relationship for all analyses (Pearson's *r* ranges = -.53 to .40, *ps* > .05).

Figure 1

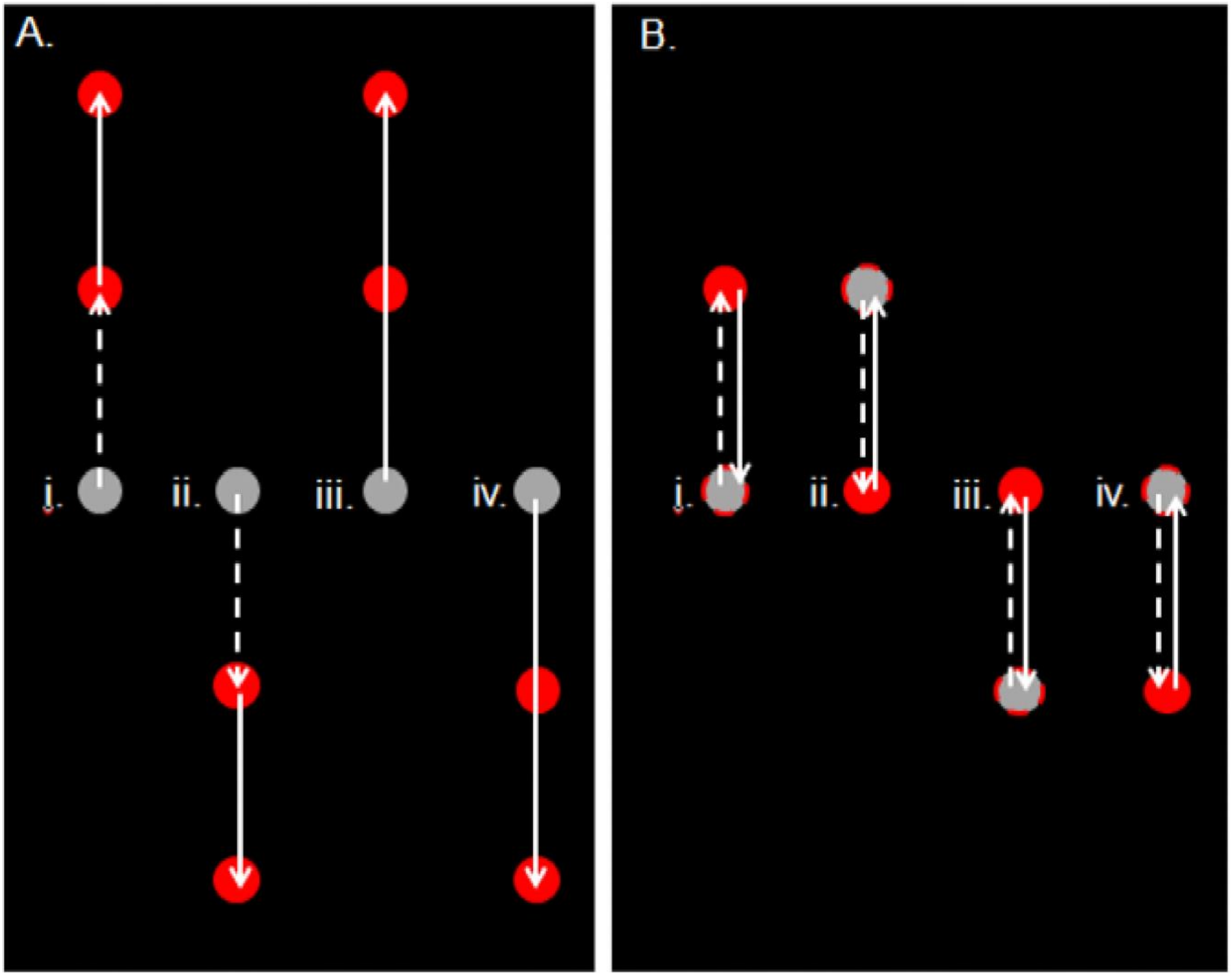


Figure 2

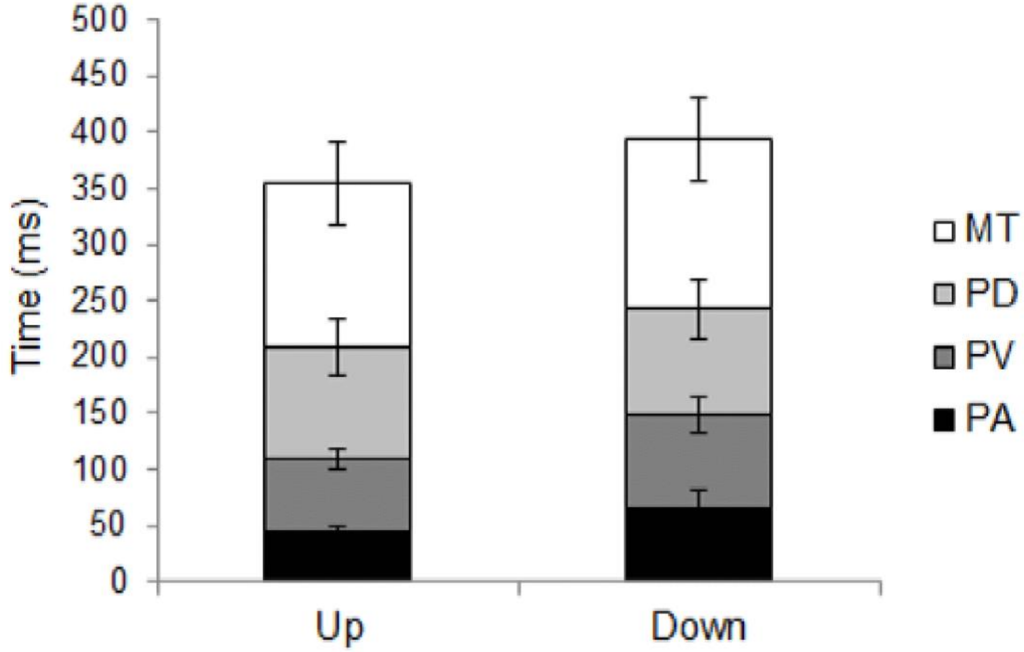
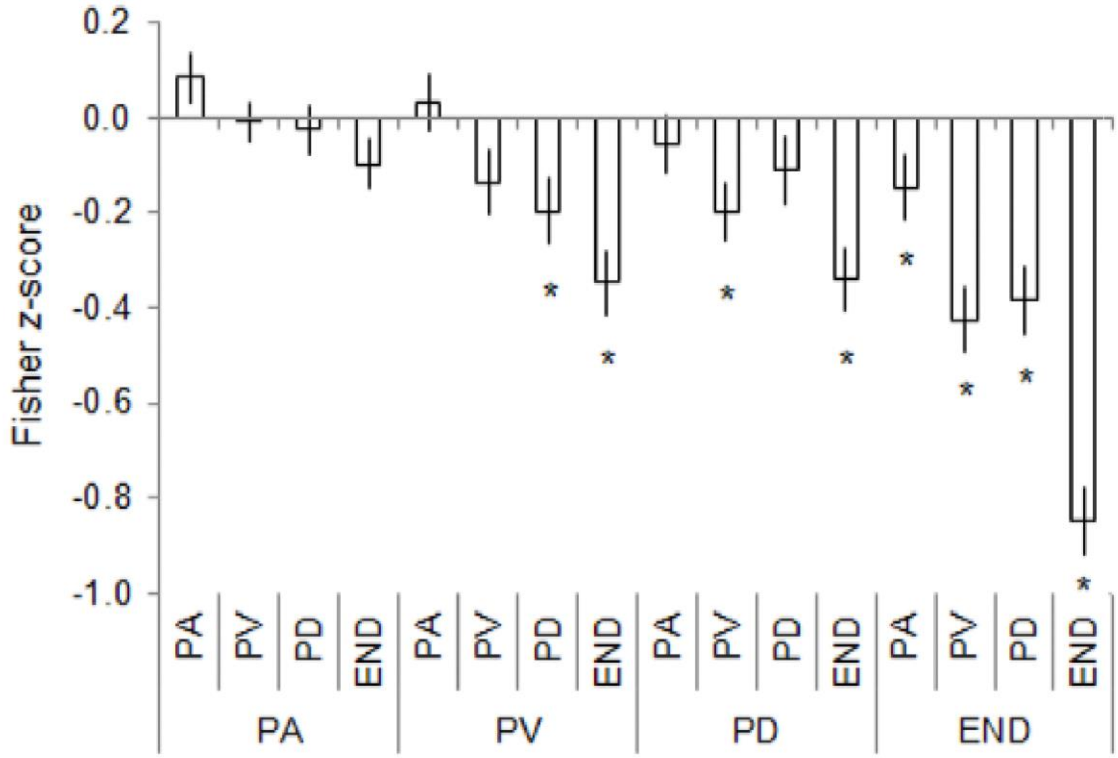
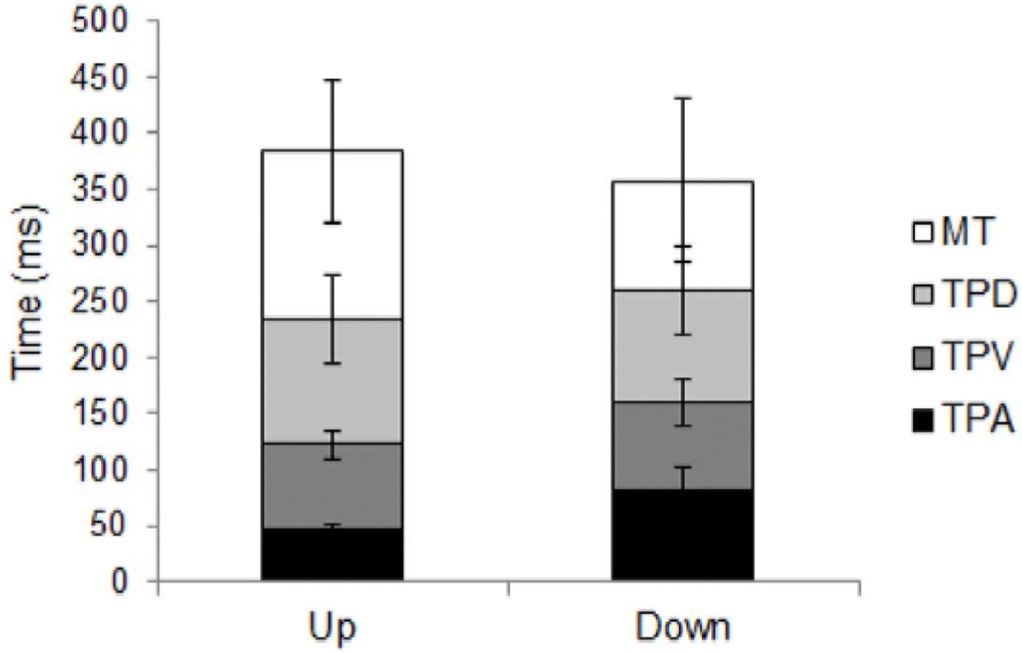

500
450
400
350
300
250
200
150
100
50
0
Time (ms)
Up
Down
MT
PD
PV
PA

Figure 3



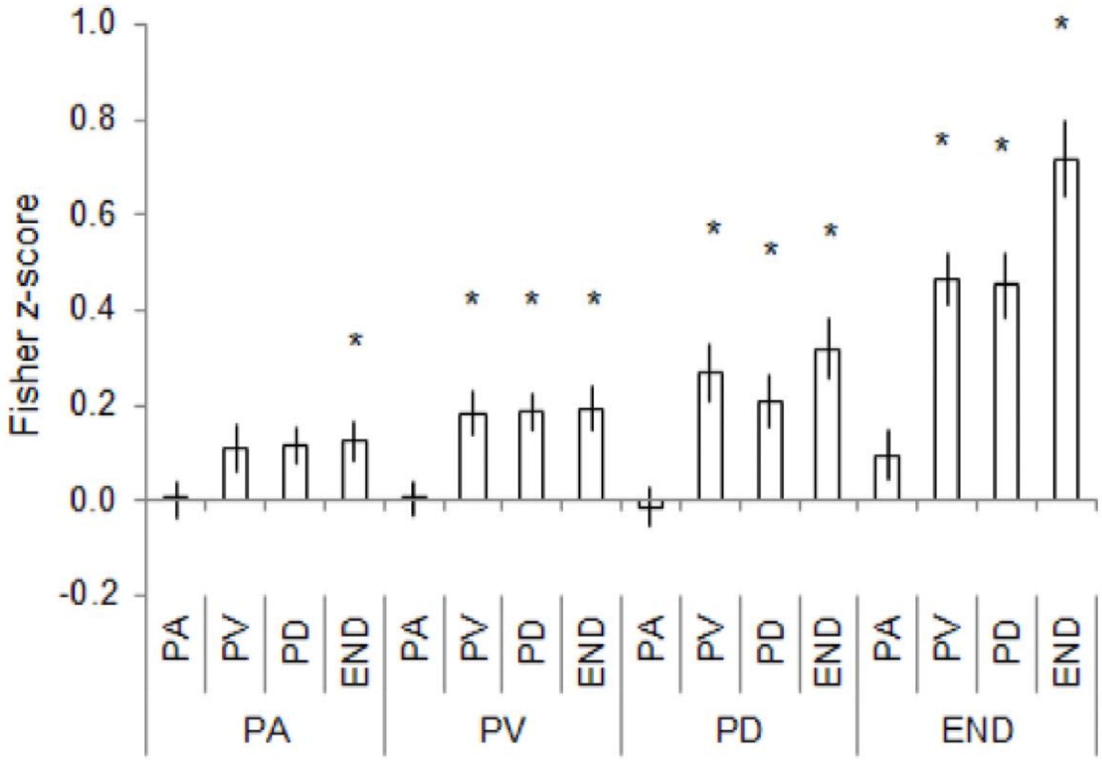
Fisher z-score
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
PA
PV
PD
END
PA
PV
PD
END
PA
PV
PD
END
PA
PV
PD
END
PA
PV
PD
END

Figure 4



500
450
400
350
300
250
200
150
100
50
0
Time (ms)
Up
Down
MT
TPD
TPV
TPA

Figure 5



Fisher z-score
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
PA
PV
PD
END
PA
PV
PD
END
PA
PV
PD
END
PA
PV
PD
END
PA
PV
PD
END

Figure 6

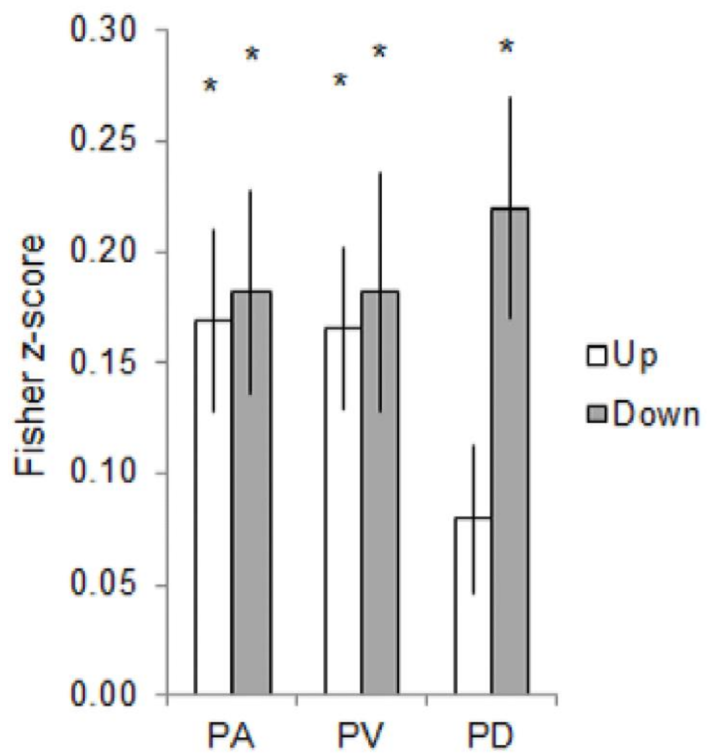
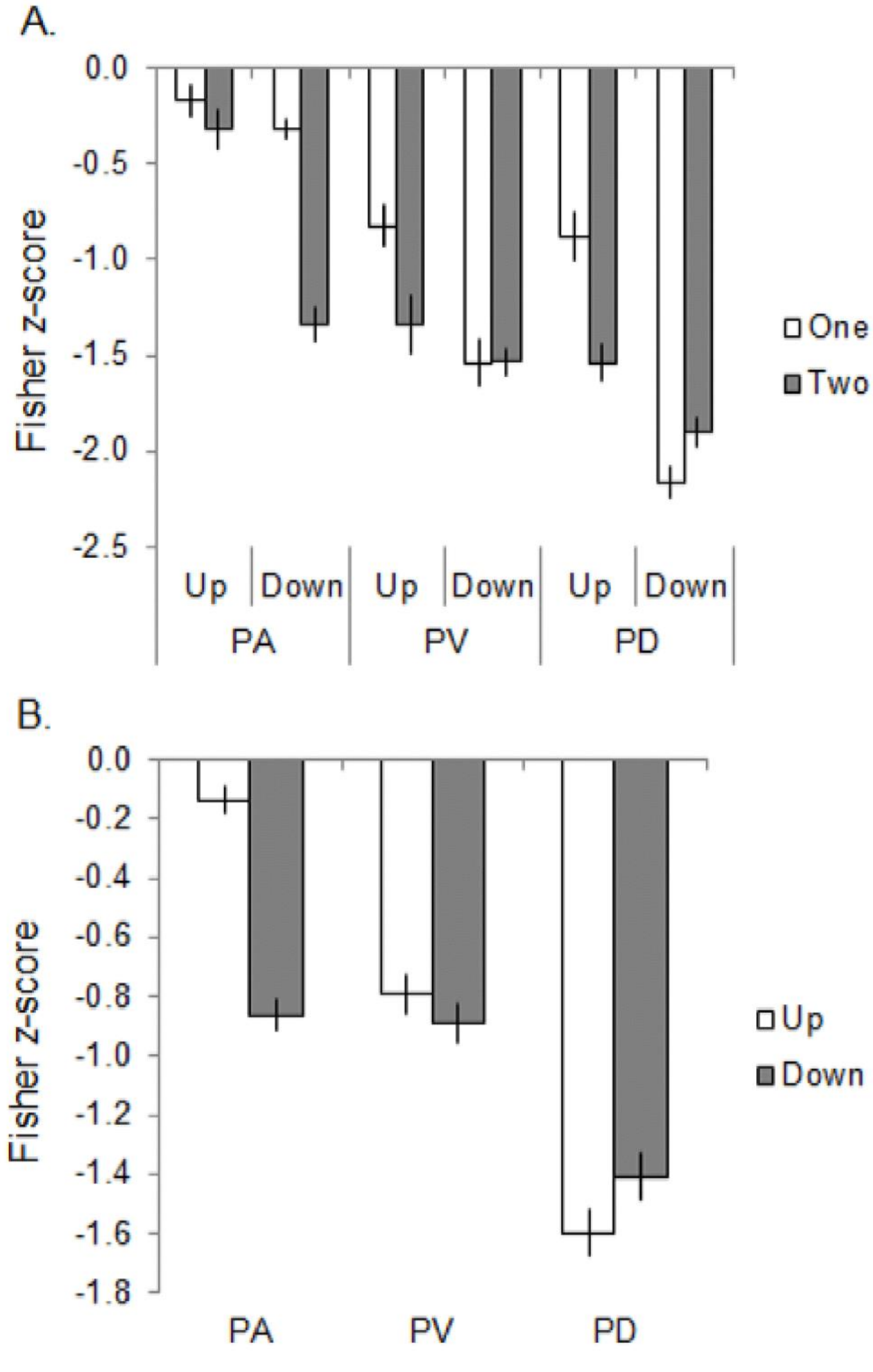


Figure 7



A.
Fisher z-score
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
Up
Down
Up
Down
Up
Down
PA
PV
PD
One
Two
B.
Fisher z-score
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
-1.6
-1.8
PA
PV
PD
Up
Down

Table 1

Exp. 1	One-component				Two-component			
	PA	PV	PD	END	PA	PV	PD	END
Up	4.9 (0.2)	31.2 (0.7)	68.3 (1.0)	78.7 (0.4)	4.9 (0.2)	31.6 (0.8)	70.0 (0.9)	78.8 (0.4)
Down	7.2 (0.7)	37.7 (0.8)	70.9 (0.5)	78.5 (0.5)	7.9 (0.6)	37.8 (0.9)	70.4 (0.8)	78.3 (0.5)

Table 2

Exp. 2	One-component				Two-component			
	PA	PV	PD	END	PA	PV	PD	END
Up	4.5 (0.3)	32.5 (1.0)	68.9 (1.3)	79.4 (0.6)	4.4 (0.3)	32.6 (0.8)	71.0 (0.8)	79.8 (0.4)
Down	9.1 (0.8)	36.2 (0.9)	67.9 (1.1)	77.9 (0.5)	8.8 (0.7)	36.4 (1.0)	67.9 (1.2)	77.6 (0.7)